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MICROMACHINED STIMULATING ELECTRODES

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MICROMACHINED STIMULATING ELECTRODES

Summary

This program seeks to develop a family of active stimulating probes for use in neural prostheses. During the last quarter, work focused in several areas. We have continued to fabricate passive stimulating probes for internal and external users and have defined an improved site structure that should provide improved reliability and yield. The use of porous silicon has been demonstrated for probe fabrication as a possible alternative, or adjunct, to the present boron diffusion process. This material would allow the formation of an etch-stop under the active circuitry, would allow circuitry to be distributed on probe shanks, and, because of its low etch temperature, is compatible with the use of exposed aluminum interconnect. It seems likely that this process will be very useful in some active probe structures. We have also successfully demonstrated low resistance interconnect using both Ta and $TaSi_2$ materials. Both are able to provide desired line resistances of less than 1 ohm per square.

The fabrication of a 64-site 4-channel current steering probe, STIM-2B, is continuing and is expected to be completed in the next few weeks. This probe will also be available in a 3D version. For this, a platform has been designed with programmable fuses that allow it to be easily adapted to either partially- or fully-populated arrays. Design options for the full-3D probe, STIM-3, are being reviewed to maintain a low implant profile and high performance. It is expected that after the realization and testing of STIM-2B/3B, fabrication will begin on these high-end devices.

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1. Introduction

The goal of this research is the development of active multichannel arrays of stimulating electrodes suitable for studies of neural information processing at the cellular level and for a variety of closed-loop neural prostheses. The probes should be able to enter neural tissue with minimal disturbance to the neural networks there and deliver highly-controlled (spatially and temporally) charge waveforms to the tissue on a chronic basis. The probes consist of several thin-film conductors supported on a micromachined silicon substrate and insulated from it and from the surrounding electrolyte by silicon dioxide and silicon nitride dielectric films. The stimulating sites are activated iridium, defined photolithographically using a lift-off process. Passive probes having a variety of site sizes and shank configurations have been fabricated successfully and distributed to a number of research organizations nationally for evaluation in many different research preparations. For chronic use, the biggest problem associated with these passive probes concerns their leads, which must interface the probe to the outside world. Even using silicon-substrate ribbon cables, the number of allowable interconnects is necessarily limited, and yet a great many stimulating sites are ultimately desirable in order to achieve high spatial localization of the stimulus currents.

The integration of signal processing electronics on the rear of the probe substrate (creating an "active" probe) allows the use of serial digital input data which can be demultiplexed on the probe to provide access to a large number of stimulating sites. Our goal in this area is to develop a family of active probes capable of chronic implantation in tissue. For such probes, the digital input data must be translated on the probe into per-channel current amplitudes which are then applied to the tissue through the sites. Such probes generally require five external leads, virtually independent of the number of sites used. As discussed in previous reports, we have designed a series of active probes containing CMOS signal processing electronics. Two of these probes have been completed and are designated as STIM-1A and STIM-1B. A third probe, STIM-2, is now undergoing a final iteration and is a second-generation version of our original high-end first-generation design, STIM-1. All three probes provide 8-bit resolution in digitally setting the per-channel current amplitudes. STIM-1A and -1B offer a biphasic range using ±5V supplies from 0μA to ±254μA with a resolution of 2μA, while STIM-2 has a range from 0 to ±127μA with a resolution of 1μA. STIM-2 offers the ability to select 8 of 64 electrode sites and to drive these sites independently and in parallel, while STIM-1A allows only 2 of 16 sites to be active at a time (bipolar operation). STIM-1B is a monopolar probe, which allows the user to guide an externally-provided current to any one of 16 sites as selected by the digital input address. The high-end STIM-2 contains provisions for numerous safety checks and for features such as remote impedance testing in addition to its normal operating modes. It also offers the option of being able to record from any one of the selected sites in addition to stimulation. It will be the backbone of a multi-probe three-dimensional (3D) 1024-site array (STIM-3) now in development. A new probe, STIM-2B, is currently being added to this set. It offers 64-site capability with off-chip generation of the stimulus currents for four separate channels. These channels are organized in four groups so that each current can be directed to any of the 16 sites in its group, and the site can be programmed for either stimulation or recording. This probe will be available in both 2D and 3D versions (as STIM-2B/3B).

During the past quarter, we have continued to fabricate passive probe structures for internal and external users. Work to define a more reliable site structure has been completed and is being reported in a companion report on "Thin-Film Intracortical Recording Microelectrodes." We are continuing to explore the use of porous silicon as a sacrificial layer in probe formation, and a low-resistance interconnect has been developed using Ta and $TaSi_2$ for use with the probes. The STIM-2B/3B probes are still in fabrication but are now nearing completion. Test results are expected during the coming term. The results in each of these areas are described more fully in the sections below.

2. *Porous Silicon Micromachining Process Development*

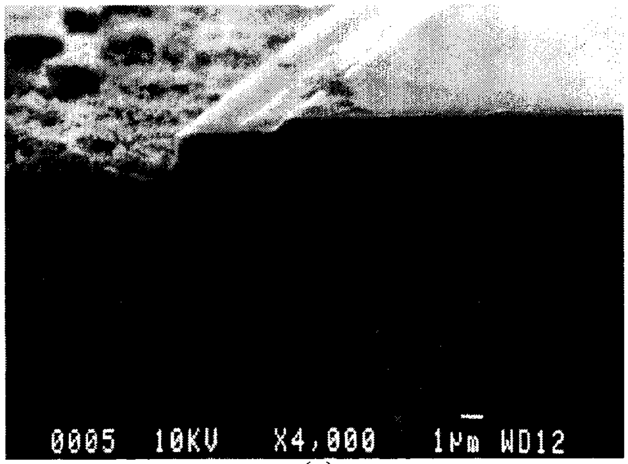
We have continued to explore the use of porous silicon as a micromachining tool to be used with, or as a possible alternative to, high-concentration boron diffusion etch-stops. Porous silicon, as discussed in the previous report, is formed under bias in hydrofluoric (HF) acid. Its primary advantage is that it provides an etch-stop without the need for heavily-doped regions. Defining probes using porous silicon would allow for the fabrication of circuitry anywhere on the devices (e.g., on the shanks themselves) and would provide an etch-stop under circuit areas. The lack of this type of an etch-stop in our current active probe process has been a primary factor limiting active probe yield.

In the process that is under development, porous silicon is used as a sacrificial layer in the field and underneath probes. It is formed at the beginning of the process, and all standard processing steps are subsequently performed on top of the porous layer. As the final step in the process, the porous layer is removed in room-temperature KOH, which does not attack the bulk silicon probes. The probes are defined by the selective formation of pores on one side of a pn-junction. Thus, probe substrates may be either p-type or n-type silicon in a wafer of the opposite dopant type. One option for forming the probe regions was discussed in the previous report and involves epitaxial silicon growth and planarization. While this method allows for fairly thick devices to be created, it is significantly more complex than our current process. An alternative, and much simpler, method would be to define the probes by an ion implant and subsequent drive-in, both of which are standard steps in foundry processing.

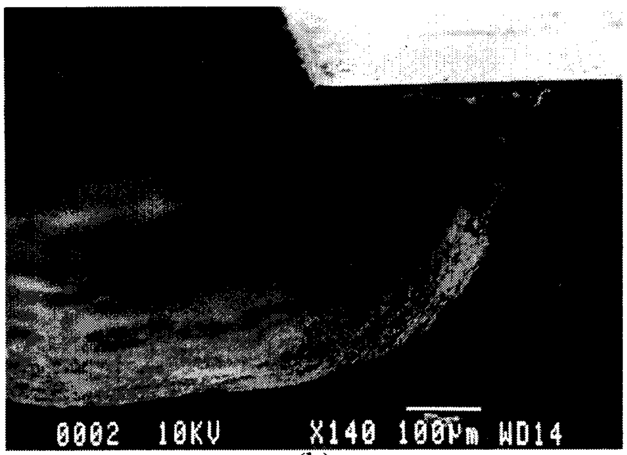
Figure 1 shows the progression of the porous silicon micromachining process. In Fig. 1a, a cross-section is seen in which a p-type bulk silicon region is surrounded and undercut by pores in the n-type field. The p-type region was masked with nitride while the sample was anodically etched to form the porous sacrificial layer. In Fig. 1b, the porous silicon has been removed from a similar structure in room-temperature KOH, partially releasing the p-type structure from the wafer. Figure 1c shows two probe shanks which have been defined and released by the formation and removal of a porous silicon sacrificial layer. A mask set is currently being designed which incorporates access holes every 200μm to facilitate complete lateral undercutting of the probe structures.

Low-Resistance Interconnect

We have begun to use low-resistance refractory metal as an alternative to polysilicon for probe interconnect lines. Both pure tantalum (Ta) and tantalum silicide ($TaSi_2$) have been investigated for this purpose. $TaSi_2$ is formed by co-sputtering Ta and Si, followed by a high-temperature (850°C) anneal to allow the two materials to react and form a silicide. Pure Ta is also deposited by sputtering, but there is no subsequent annealing step needed.



(a)



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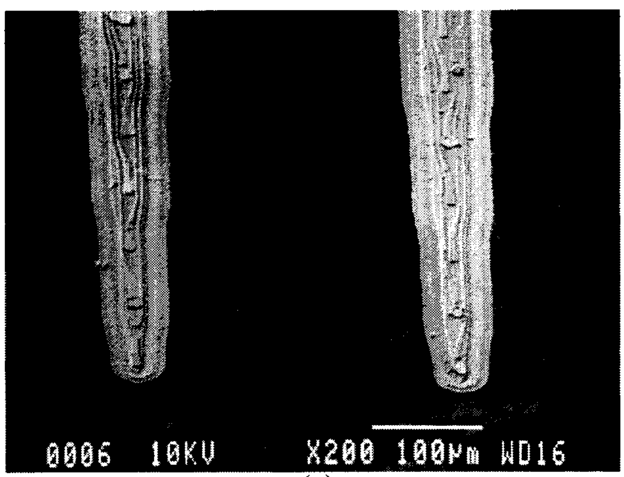

(c)

Fig. 1: SEM photographs showing the micromachining steps in the fabrication of probes using a porous silicon sacrificial layer. (a) An n-type porous layer surrounding and undercutting a p-type probe substrate. (b) A similar structure following the removal of the porous sacrificial layer in KOH, resulting in a partially released probe substrate. (c) Probe shanks defined and released using this micromachining technique.

We are able to achieve, with both materials, our target sheet resistance of 1 ohm/square. We found pure Ta to be slightly lower in resistivity (50 μohm-cm) than $TaSi_2$ (60 μohm-cm), although not as much lower as would be expected, due to the resulting crystal structure of sputtered Ta. With pure Ta, a line thickness of approximately 6000Å yields a sheet resistance of 0.9 ohms/square. The same sheet resistance is achieved in $TaSi_2$ with a line thickness of approximately 7000Å.

2. *Active Stimulating Probe Development*

During the past quarter, work on active stimulating probe development has primarily focused on the fabrication of the STIM-2B/STIM-3B probe mask set, which is a 16 mask process which includes the deep/shallow boron CMOS process and the 3-mask site process. Also, work was started on the layout of the structures necessary for the 3-D arrays, STIM-3B. All of the various structural pieces for STIM-3B were completed: the platform/ribbon cable and the spacers. Also, an interconnect scheme was developed such that a single platform design can be used to realize a partially- or fully- STIM-3B array with array programmability via air-bridge fuses.

STIM-2B

The second-generation, four-channel, 64-site active stimulating probe, STIM-2B, is currently nearing completion in the fabrication run. We anticipate that the completion of this design will give us an important tool in for use in performing some very important and interesting experiments by allowing the acute and chronic stimulation access to a relatively large volume of neural tissue without repositioning the probes.

In order to realize this capability, the design utilizes a 20b shift register to load four 4b site addresses which are decoded by a 1-of-16 nand-type decoder to connect the designated site to an analog input/output pad through a large CMOS passgate transistor, thereby allowing the 'steering' of externally generated currents to the addressed site. A fifth bit has been included along with the 4b site address in order to allow selection between the stimulation mode and a newly added recording function. This fifth bit simply selects between either a direct path to the I/O pad from the site or a path through an amplifier for recording from the same site. There is a total of four on-chip amplifiers, one for each I/O channel.

One of the most important features of this probe design is its almost completely digital design. Essentially the only analog portions of the STIM-2B probe design are amplifiers. The design is such that if the amplifiers do not function exactly as designed due to such things as bias changes resulting from process variations, the probe will still function normally in the stimulation mode. The simplicity and digital nature of the STIM-2B design lends itself to a very robust design.

The fabrication of STIM-2B as it currently stands is shown in Fig. 2. The interconnect/gate polysilicon has been deposited and patterned and the devices are ready for the source/drain implants. These devices should be completed within the next couple of weeks.

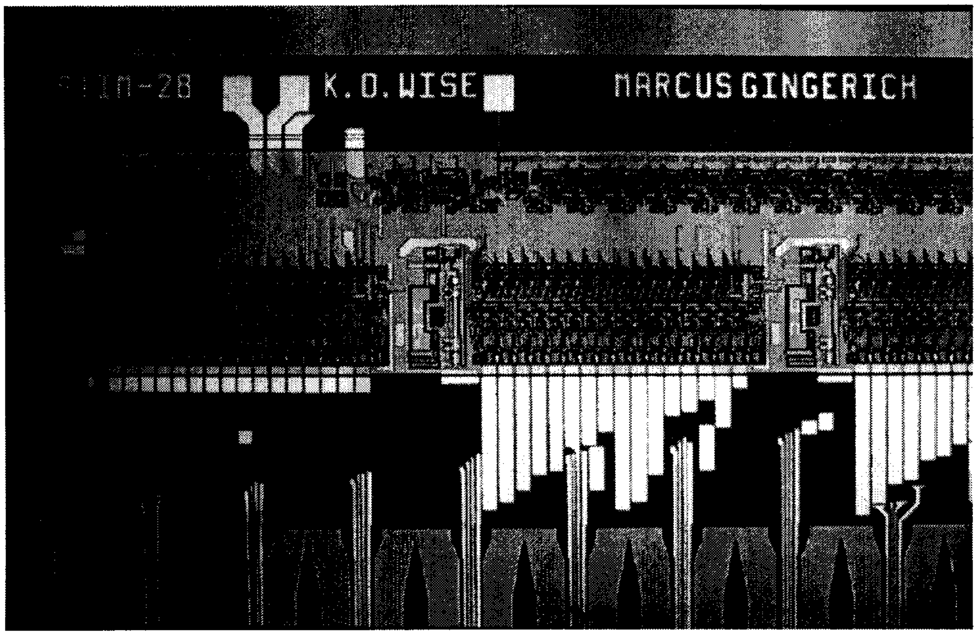

Fig. 2: A partial die microphotograph of the STIM-2B probe design as it appears in the current stage of the fabrication process.

STIM-3B

The 3-dimensional probe that has been referred to as STIM-3B is an extension of the 2-D probe, STIM-2B. There are no great changes in the designs --- simply some structural differences in the probe geometry to accommodate assembly and connection with a platform assembly and the minimum of circuit enhancements as necessary to allow addressing of multiple probes in a 3-D array.

The required changes in structure include the wings and the beam-lead interconnects for assembly and lead transfer from the individual probes to the 3-D platform. The wings also incorporate 45° angled slots to ensure that the wings will etch clear in the final probe release step, thus allowing the spacers of the 3-D assembly to properly fit down over them. The 45° angled slots were designed such that a continuous trench would be etched from the front side of the probe even before the etch plane advances from the backside during the final release etch in EDP. As discussed in the previous report, the integrity of the circuit area was ensured by making the surrounding deep boron diffused rim wide enough so that the lateral undercut from the corners does not have time to reach the active circuit area. Also, a newly developed technique for protecting the circuit corners, which uses small dielectric bridges and the anisotropy of the EDP etchant, was also included at the full wafer layout level. The etch-out test results as discussed in depth in the last report showed that the corner protection technique is very effective. Finally, the use of deep-RIE-etched slots around the probe wings and shanks can assist in ensuring that these areas are released prior to the circuit areas as described in the present report on recording probe development.

The circuit changes necessary to realize a 3-D probe were kept to a minimum in order to keep the circuitry as simple as possible while still allowing maximum flexibility of the 3-D probe system. The necessary circuit changes include a 4b shift register of which each bit is used as a flag bit to select/de-select an I/O line via a large CMOS passgate placed in the line. The last bit of the shift register was also buffered out onto an additional lead to go off probe. The 3-D probe system operation is then quite simple. The probes of the 3-D array all share common analog I/O data lines, power lines, clock lines and y-addr (normal probe address) lines. The same y-addr is clocked into the 20b shift register on all of the individual probes.

The key to the design is that while the same y-addr is being clocked into all the probes, an x-addr (I/O channel enable) is simultaneously being clocked into the first probe and daisy-chained through the second, third, and nth probe via interconnecting leads on the platform, thereby making an extended 'virtual register'. Differing numbers of probes in the array only result in differing x-addr lengths, and it is only necessary to be sure that the last bits of both the y-addr and x-addr arrive at the same time. As will be discussed in more depth later, the platform has been designed using air-bridge fuses such that any number of probes can be used in the platform in any position and the common platform design can be 'programmed' to accommodate the different configurations via the fuses.

The resulting system is requires ten leads that can select almost any combination of four sites across the array. The design allows for variable array size via the 'programmable' platform, and it also allows inter-probe stimulation. The one weakness in the design is the fact that the same I/O channel cannot be driven on more than one probe simultaneously with an independent stimulus current. Selection of the same channel on more than one probe would result in sharing of the stimulus current between the selected probes because of the bus-type connection. Given the tradeoff between flexibility and simplicity, this design was chosen because it is still quite flexible with little increase in complexity.

The fabrication of STIM-3B as it currently stands is shown in Fig. 3. The important 45° angled slots can be seen in the boron diffused areas. The layout of the 3-D platform, spacer and a single probe is shown in Fig. 4. The platform layout also shows the interconnect scheme and the fuses for 'programming' the platform. The fuses provide a direct connection between the successive x-addr in and x-addr out pads of each probe; thus, the probe does not have to be in place for the x-addr to continue along the platform. If a probe is to be placed in a slot, the fuse can be 'blown' by passing a large current between the appropriate pads. The thermal isolation of the air bridge ensures that the lead will 'fail' at the fuse as it overheats and melts. The fabrication process for the air bridge fuse is shown in Fig. 5.

The top diagram, which is a mid-line cross-sectional slice through the layout shown in the bottom diagram, shows the patterning and wet etching of contacts through the top passivation layer down to the first conductor level using the contact mask. The first conductor mask has already been previously used to pattern the first conductor. The second diagram shows the patterning and deposition of the second conductor. The third diagram shows the structure after the final EDP etch-out in which the first conductor must be a material that it is attacked by the EDP etch where exposed and the second conductor must be resistant to EDP attack. Aluminum and gold could be used for first and second conductors, respectively.

The important feature in the third diagram is the resulting air bridge of second conductor formed when the underlying first conductor island is sacrificially etched away because of the oversized contact opening, which provides direct exposure to the EDP etchant. The fourth diagram demonstrates a blown fuse. The void of the etched out first conductor not only provides thermal isolation to ensure rapid heat up, but it also provides a well for the melted conductor to flow into thereby reducing the possibility of the lead reconnecting upon cooling and solidifying.

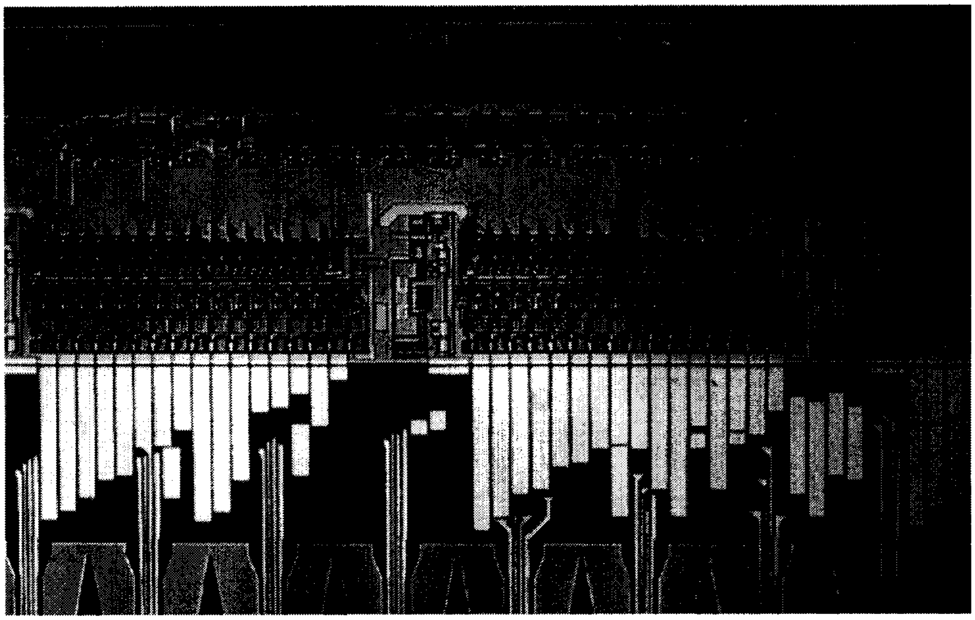

Fig. 3: A partial die microphotograph of the STIM-3B probe design as it appears in the current stage of the fabrication process.

STIM-3

The most extensive active stimulation probe to be designed under this contract is referred to as STIM-3. This probe is to be an extension of the STIM-2 probe to a 3-D array. STIM-3 is required to be an array of at least eight probes with sixteen shanks and four stimulating sites per shank: a total of 512 stimulating sites. The simplest method of realizing this array is to alter the structure of our STIM-2 probe so that it can be used to interface into a 3-D platform in the same manner as the STIM-3B array. A cartoon of the 3-D system is shown in Fig. 6. The back end circuitry portion of the probe is connected to the front end and shanks via angled shallow boron ribbon cables. The ribbon cables allow the circuit to be bent down achieving a very low profile. The ribbon cables are angled so that they undercut quickly from the front side during the final EDP release etch. Interconnection is made to the platform and an integrated ribbon cable via beam leads.

The power and clock leads would be common to all eight probes, but each probe would have a separate data lead. This would result in a total of 12 leads, the current limit of the simple percutaneous connector technology we are using. The drawback of this kind of system is that it requires a much more extensive external system since there would have to be eight synchronized external channels to address the eight separate probes.

There are several other implementations being considered as well. One would be a hybrid system in which a mux/demux chip would be included on the platform to direct serial data stream to the appropriate probe and back to the external system as necessary. This type of system would almost surely be required for any array beyond the eight probe size, i.e., a sixteen-probe 1024-site array. There is also the possibility of including an address on each of the probes. This method is readily possible since the STIM-2 probes are already designed with an extended data word mode. The main problem with this method is that the extended word mode doubles the time required to access a given probe. This may not be a problem if the probes can be designed to operate at a high enough clock rate. These different options are being considered carefully to ensure that the optimal balance of performance and simplicity is found.

During the coming quarter, the current fabrication run of STIM-2B/STIM-3B probes will be completed and tested. The system design of the STIM-3 array will be completed and the layout done. With the completion of probes, we also plan to begin some significant *in-vivo* testing and experimentation.

3. *External Stimulating Interface System Development*

We are implementing an external electronic system as an interface between a host computer and an active stimulating probe. The concept and design of this system have been discussed in previous reports. During the past quarter, we have completed the implementation of a system prototype on a wire-wrap carrier. The majority of the effort, however, has been spent in testing the prototype system and in writing firmware and software in support of this testing activity.

A large majority of the system hardware has been successfully tested. A few problems with the design details were identified and corrected, but no major design flaws were found. The use of programmable logic in key parts of the system was advantageous since hardware changes were kept to a minimum and most changes were implemented by simply reprogramming the logic devices. Although the wire-wrap carrier technology limited our testing to low-speed operation, we are confident that an eventual implementation on a printed circuit board carrier will enable full-speed operation.

The software development aspect of testing comprised three programs: a small bootloader, the main external system support program, and a support program that runs on the host computer. The bootloader program is responsible for performing basic system tests and accepting a subsequent download of the main program. The main external system program will eventually be responsible for all aspects of stimulation and communication with the host. For the moment, this program simply acts as a monitor and allows basic access and control over the external system resources. The host computer program is responsible for sending both the bootload code and the main program code to the external system, and for subsequent communication between the host computer and the external system.

During the next quarter, we expect to complete the testing of the external system hardware. We will also begin development of more robust and functional software for both the external system and the host computer. These software components will provide a user interface to generating pulsatile stimulation waveforms. Eventually, we expect to provide a graphical user interface for this task for improved ease of use.

4. *Conclusions*

This program seeks to develop a family of active stimulating probes for use in neural prostheses. During the last quarter, work focused in several areas. We have continued to fabricate passive stimulating probes for internal and external users and have defined an improved site structure that should provide improved reliability and yield. The use of porous silicon has been demonstrated for probe fabrication as a possible alternative, or adjunct, to the present boron diffusion process. This material would allow the formation of an etch-stop under the active circuitry, would allow circuitry to be distributed on probe shanks, and because of its low etch temperature is compatible with the use of exposed aluminum interconnect. It seems likely that this process will be very useful in some active probe structures. We have also successfully demonstrated low resistance interconnect using both Ta and $TaSi_2$ materials. Both are able to provide desired line resistances of less than 1 ohm per square.

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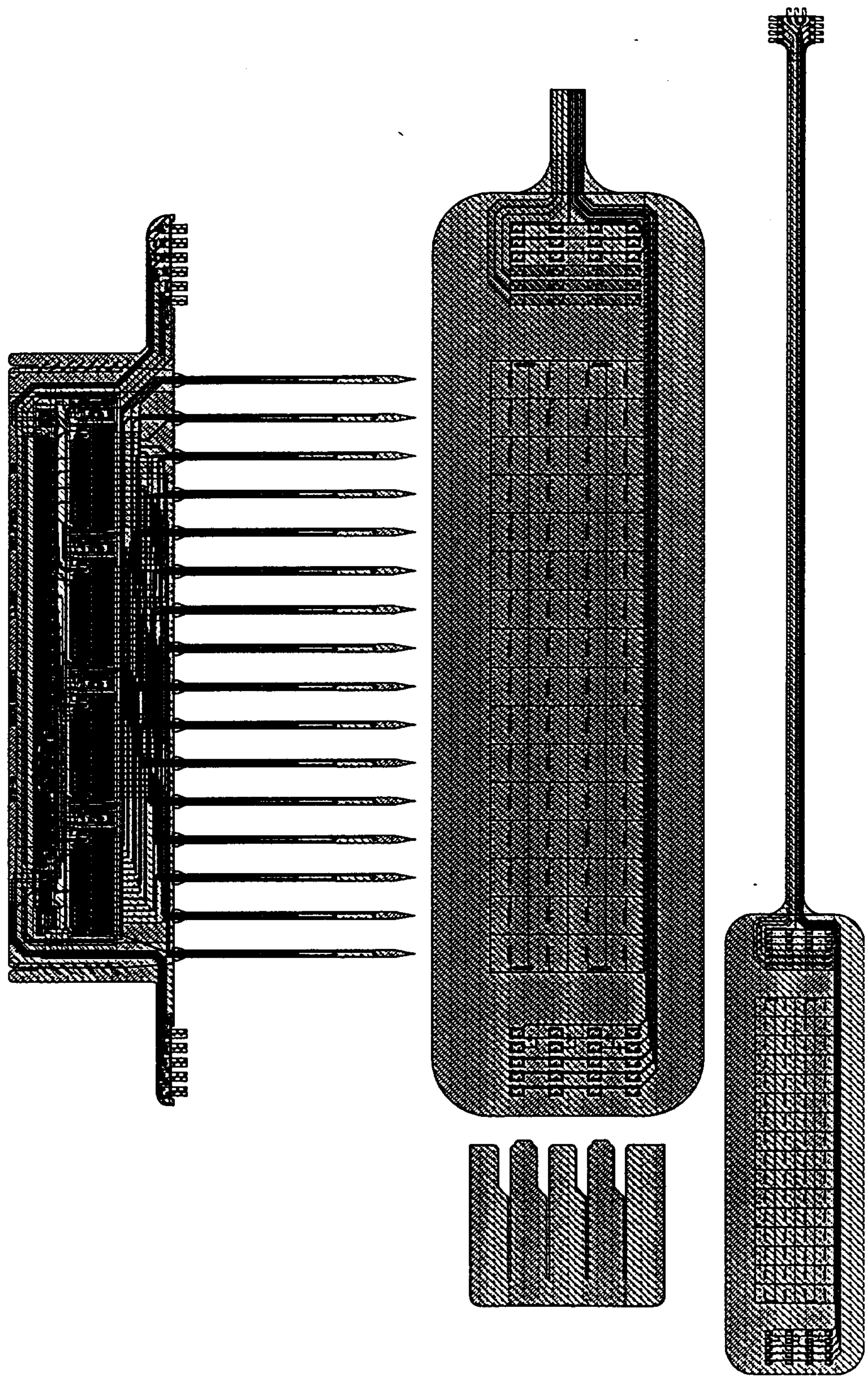

Fig. 4: The layout of the 3-D platform, spacer, and STIM-3B probe. The fuse linked interconnect scheme can be seen on the platform.

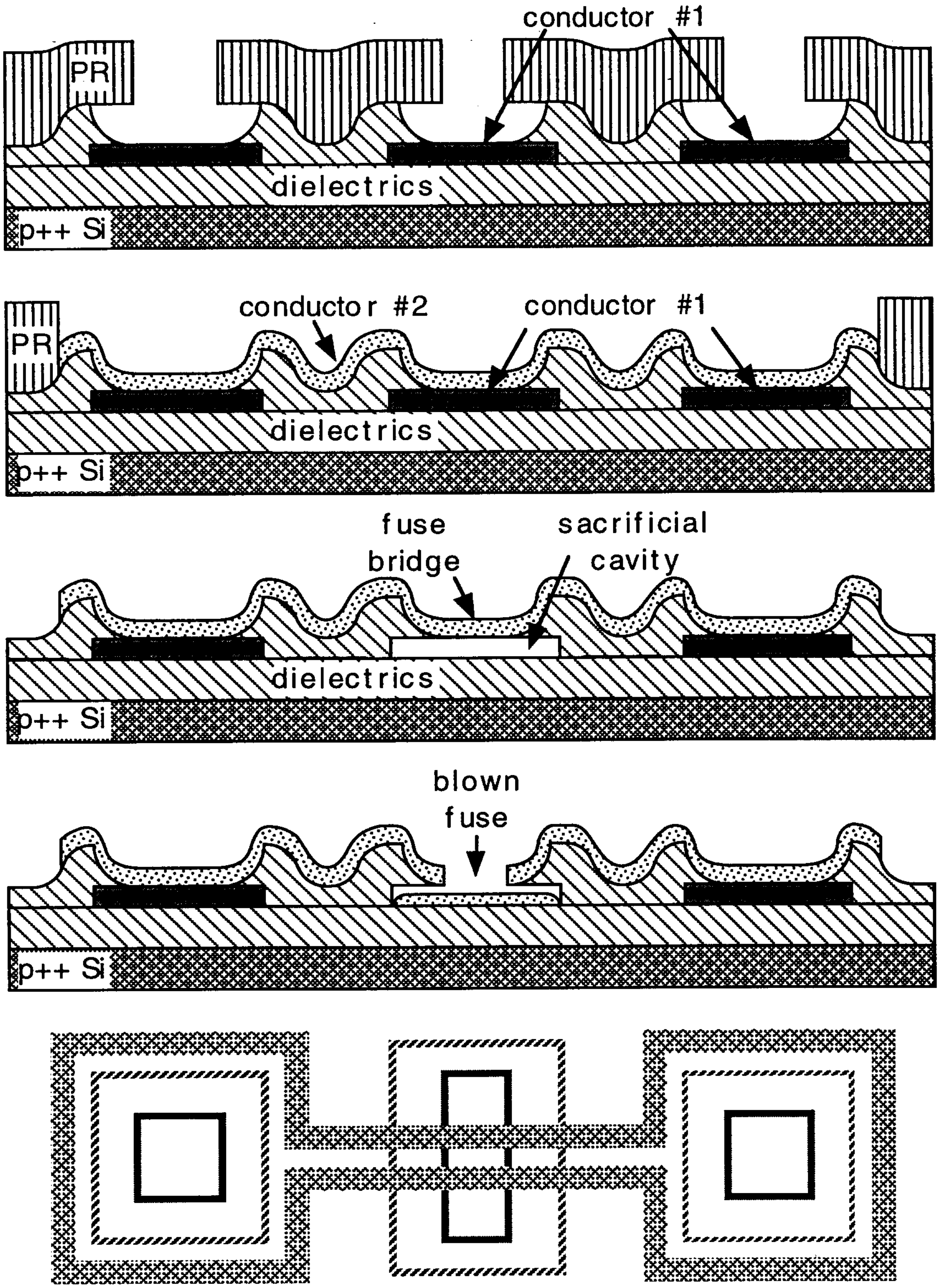

Fig. 5: The fabrication process of the air bridge fuse, which is used on the 3-D platform for 'programmability;' from top to bottom: 1) patterning and etching of contacts, 2) patterning and deposition of the second conductor, 3) formation of the air-bridge fuse by sacrificial removal of first conductor island during EDP etch, 4) blown fuse. The associated mask layout is demonstrated in the bottom diagram.

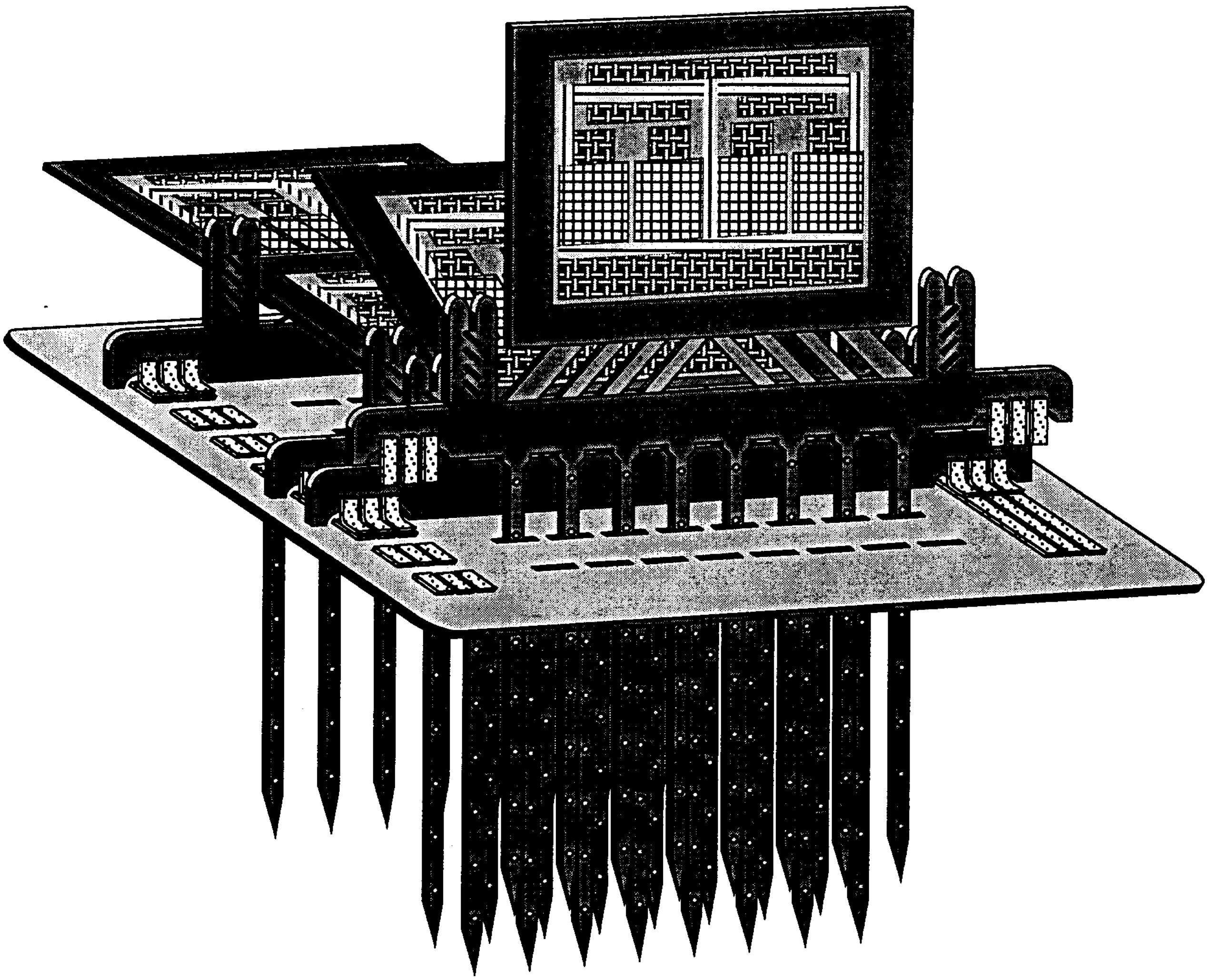

Fig. 6: A cartoon of the expected 3-D assembly of the STIM-3 active array.